Generation of millimeter-wave sub-carrier optical pulse by using a Fabry-Perot interferometer

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A novel scheme is proposed to transform a Gaussian optical pulse to a millimeter-wave (mm-wave) frequency modulation pulse by using a Fabry-Perot interferometer (FPI) for radio-over-fiber (ROF) system. It is shown that modulation frequency of mm-wave is determined by the optical path of the Fabry-Perot (F-P) cavity, and amplitude decay time and energy transfer efficiency are related to the reflectivity of the F-P cavity mirror. The effect of pulse train extension on inter-symbol interference is also discussed.

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As mobile communication and relative technology developing, demand on frequency of the wireless carrier increases rapidly, and millimeter-wave (mm-wave) wireless system is considered to be a promising candidate[1,2]. To utilize the ultra-broad bandwidth of optical fiber, radio-over-fiber (ROF) technology or microwave photonics has become a hot research and development topic. Due to the high frequency, incorporation of mm-wave signal with an optical carrier is a key subject to study. Impairment caused by fiber dispersion at such a high frequency is another important problem to be solved. Apart from the methods based on heterodyne[3,4], which was active methods, schemes using passive components were also investigated. Levinson *et al.*[5] put forward a method of generating complex frequency modulated microwave and mm-wave pulses by using dispersion and Kerr effect in optical fiber systems. Recently, they also demonstrated[6] a broad mm-wave modulated pulses generation with a linear frequency chirp by using two fiber Bragg gratings (FBGs) and a mode-locked fiber laser. McKinney research group reported the arbitrary waveform mm-wave pulse generation by a direct space-to-time pulse shaper, such as diffraction grating[7] and virtually imaged phased-array (VIPA)[8], but the systemic schemes are all relative complex to bring into effect in practical manipulation. Moreover, we have proposed a fix-frequency modulation mm-wave pulse generation scheme by using an apodized Moiré fiber grating in the previous work[9]. The method has a mature technology and low-cost.

In this letter, we propose another novel scheme to transform a Gaussian pulse to a mm-wave frequency modulated pulse by using a Fabry-Perot interferometer (FPI) filter. Compared with the method using FBG, this scheme provides a possibility of tuning the mm-wave sub-carrier frequency, which is quite important and attractive in practical application.

Principle of the proposed scheme can be understood in following two points of view. In temporal domain, an input short pulse is transmitted and reflected at the two mirrors of Fabry-Perot (F-P) cavity repeatedly, and output a train of optical pulse with a repetition rate decided by the cavity length. In frequency domain, an input pulse with an original spectrum is filtered by the multi-peak spectrum of the F-P filter; and the output spectrum is changed to that with two or more peaks, which will beat each other and generate a mm-wave or microwave frequency modulated optical pulse envelope. For quantitative analysis, spectral analysis will be used in the following simulation; and for simplicity a Gaussian pulse is taken as an example, whose waveform and spectrum can be expressed as

$$E_0(t) = A\exp(-t^2/2\tau^2)\exp i\omega_0 t, \quad (1)$$

$$\widetilde{E}_0(\omega) = \sqrt{2\pi}A\tau\exp[-(\omega-\omega_0)^2\tau^2/2), \quad (2)$$

where ω_0 is the central angle frequency, τ is the $1/e$ width of optical intensity. The transmission spectral response function of FPI can be written as

$$\chi(\omega) = \frac{T\mathrm{e}^{i\phi}}{1-R\mathrm{e}^{i2\phi}}, \quad (3)$$

where T and R are the transmission index and reflectivity of the two F-P mirrors, $\phi = 2\pi nd/\lambda$ is the phase shift of a round trip traveling, with an equivalent time delay of $\Delta T = 2nd/c$, d and n are the length and refractive index of F-P cavity, respectively. Now the spectrum of output pulse may be obtained by a relation of $\widetilde{E}_{\mathrm{out}}(\omega) = \chi(\omega)\widetilde{E}_{\mathrm{in}}(\omega)$, and the output waveform can be obtained by relative Fourier transform.

While an explicit analytic expression of the transform waveform is not available, numerical simulations are easy to fulfill. Parameters d = 1.6 mm, n = 1.5, λ = 1550 nm, τ = 3 ps, and $\sqrt{R}$ = 0.95 are used in the following calculation. Figure 1 shows the output pulse waveform, which is composed of a train of repeated pulses, and can be regarded as a mm-wave pulse with a modulation frequency of 62.5 GHz and wavelength of 4.8 mm, according to the basic relation of $f = 1/\Delta T$. A high-speed optical-to-electrical conversion may be used to obtain mm-wave radio frequency (RF) signal.

It is shown in Fig. 1 that the amplitude decay of the individual pulse in the train satisfies the function of $I(t) = I_0\exp(-t/T_{\mathrm{d}})$, which is caused by multiple reflections. The decay time can be evaluated as

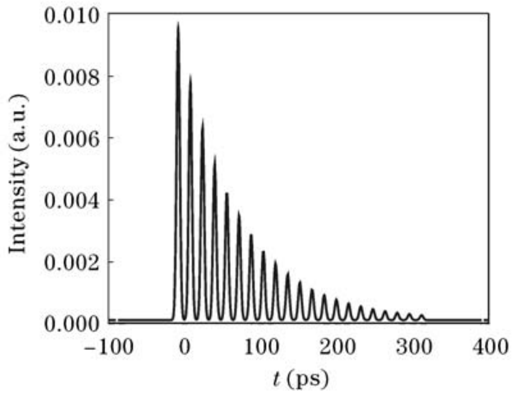

Fig. 1. Output pulse from a FPI.

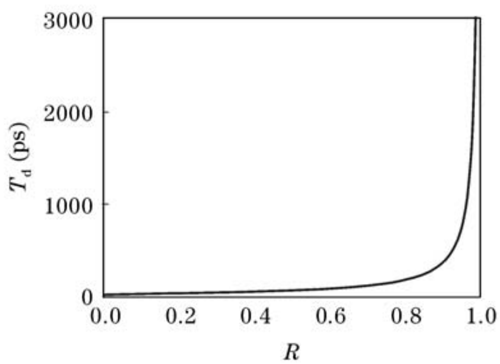

Fig. 2. Decay time of output pulse versus the FPI reflectivity.

$$T_{\mathrm{d}} = \Delta T / (\ln R^{-1}). \tag{4}$$

Obviously higher reflectivity of the F-P cavity mirror and larger optical path of the F-P cavity will generate longer mm-wave pulse, as shown in Fig. 2.

On the other hand, the integrated energy of the output decreases with the reflectivity increasing. It is because that the first reflection at incidence to the F-P input mirror makes a large loss, and also multiple losses at every reflection of backward beams. The conversion efficiency from input to output can be deduced as

$$\eta = (1 - R)/(1 + R). \tag{5}$$

Therefore a tradeoff reflectivity has to be selected for higher energy efficiency and flatter top mm-wave signals.

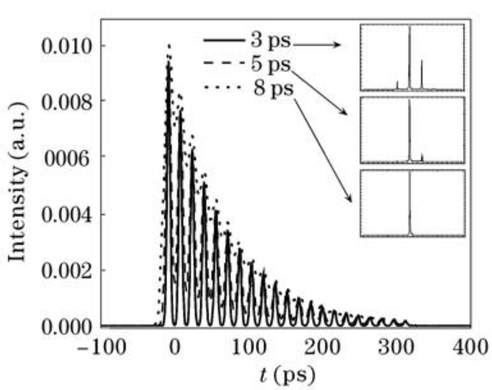

Fig. 3. Output pulse versus the different initial input pulse widths.

Pulse width τ of the input will affect the output waveform greatly. Figure 3 shows simulated results when the input pulse widths are taken to be 3, 5, and 8 ps, respectively, which is understandable by means of pulse overlapping. In the frequency domain, the phenomenon is related to the number of beat wavelengths. The insets in Fig. 3 are the relative spectra of output pulse for input pulse widths. Larger input pulse width leads to narrower spectral width, and results in lower extinction ratio and lower mm-wave power, which may be understood by the following qualitative analysis. From Fig. 3, the middle intensity of the adjacent peaks may be written as

$$\begin{aligned} I_{\mathrm{mid}} &= \Big| E_j(t_j + \Delta T/2)\mathrm{e}^{i\phi(t_j+\Delta T/2)} \\ &\quad + E_{j+1}(t_{j+1} - \Delta T/2)\mathrm{e}^{i\phi(t_{j+1}-\Delta T/2)} \Big|^2 \\ &= \Big| E_1 \mathrm{e}^{-(\Delta T)^2/8\tau^2} \mathrm{e}^{i\phi(t_i+\Delta T/2)} \\ &\quad + R E_1 \mathrm{e}^{-\Delta T^2/8\tau^2} \mathrm{e}^{i\phi(t_{j+1}-\Delta T/2)} \Big|^2 \\ &= E_1^2 \mathrm{e}^{-\Delta T^2/4\tau^2}[1 + R^2 + 2R\cos\Delta\phi], \end{aligned} \tag{6}$$

where E_j and t_j are the jth peak amplitude and related time coordinate, $\Delta\phi$ is the phase difference between the middle overlapped points for the adjacent peaks. When the output pulse from FPI is non-chirp pulse, then the phase difference $\Delta\phi$ may be described as

$$\begin{aligned} \Delta\phi &= \phi(t_j + \Delta T/2) - \phi(t_{j+1} - \Delta T/2) \\ &= \omega(t_j - t_{j+1} + \Delta T) = \omega(\Delta T - \Delta T) = 0. \end{aligned} \tag{7}$$

Therefore Eq. (6) can be simplified as

$$I_{\mathrm{mid}} = E_{j0}^2 \mathrm{e}^{-\Delta T^2/4\tau^2}(1 + R)^2. \tag{8}$$

Using Eqs. (6) and (8), the extinction ratio ε may be deduced as

$$\varepsilon = \frac{I_j + I_{j+1}}{2I_{\mathrm{mid}}} = \frac{E_1^2(1 + R^2)}{2I_{\mathrm{mid}}} = \frac{1 + R^2}{2(1 + R)^2}\mathrm{e}^{\Delta T^2/4\tau^2}. \tag{9}$$

Therefore, the extinction ratio has a close relation with the input initial pulse and optical path of F-P cavity, which should be selected properly. In order to obtain a good extinction ratio of optical-to-electrical conversion, the input spectrum should cover two or more F-P resonance peaks at least. Moreover, it is also noticed that, when the input pulse width is fixed, the central frequency ω_0 shift of input pulse will bring in little effect on the output characteristics and this is very important for practical implement.

Since the output pulse train may sustain to a relatively long time, the tail will produce inter symbol interference (ISI), which is very bad for systemic bit error rate. Consider an on-off keying format as an example and denote B as the bit rate of transmitted signal (bit period of $1/B$), the mm-wave energy in a '1' bit can be calculated as

$$Q(1) \propto I_0 T_{\mathrm{d}}[1 - \exp(-1/BT_{\mathrm{d}})]. \tag{10}$$

If its tail extends to the next '0' bit, the unwanted energy can be evaluated as

$$Q(0) \propto I_0 T_{\rm d} \exp(-1/BT_{\rm d}). \quad (11)$$

Then the ISI can be expressed as

$$\mathrm{ISI} \propto \frac{\exp(-1/BT_{\rm d})}{1-\exp(-1/BT_{\rm d})} = \frac{R^{f/B}}{1-R^{f/B}}, \quad (12)$$

where f is the mm-wave frequency. This formula sets a limit to the transmitted bit rate, and a criterion to the reflectivity.

The method proposed by using the FPI filter has a potential for mm-wave tuning by adjusting the optical path length of the FPI. Tuning possibility is very important and attractive for practical applications; related researches involve some detailed technical issues, which may be described in another paper.

In conclusion, a novel scheme has been proposed to transform a short pulse to a mm-wave frequency modulated pulse by using a FPI filter. Characteristics of the scheme, including modulation frequency, decay time, and energy efficiency, are discussed. And the effect of the initial input pulse width on the output pulse waveform is also studied. The proposed method is believed useful in ROF and microwave technologies.

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